STRUCTURE AND KINEMATICS ALONG THE THRUST FRONT OF THE TRANSVERSE RANGES: 3D DIGITAL MAPPING OF ACTIVE FAULTS IN SANTA MONICA BAY USING REFLECTION, WELL, AND EARTHQUAKE DATA: COLLABORATIVE RESEARCH WITH UNIVERSITY OF CALIFORNIA, SANTA BARBARA AND COLUMBIA UNIVERSITY

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INVESTIGATIONS UNDERTAKEN

We used industry seismic reflection and well data to construct digital structure-contour maps of faults and a deformed horizon beneath northern Santa Monica Bay. Several other stratigraphic horizons were correlated through the area. These maps include a principal strand of the Dume fault, a blind fault beneath it, and a deformed horizon within the Pliocene Repetto interval. Mapped surface faults include the NW-SE San Pedro basin fault and the E-W Malibu Coast fault. Graduate student Kris Broderick has been involved in the fault mapping and stratigraphic interpretation, and this work will comprise his UCSB Master's thesis.

Introduction

Space geodesy shows about 8-12 mm/yr of N-S contraction across the western Transverse Ranges orogen, between the San Gabriel Mountains and Long Beach, or between the mountains north of Ventura basin and an islands reference frame (Fig. 1 in Argus et al., 1999). Large reverse-slip earthquakes occurred both north and south of the Santa Monica Mountains (Fig. 1; e.g., USGS and SCEC, 1994; Gutenberg et al., 1932; Stierman and Ellsworth, 1973; Hauksson and Saldivar, 1986; Hauksson, 1990). There have also been large right-lateral earthquakes on NW-SE faults adjacent to Santa Monica Bay (Fig. 1; Wood, 1933; USGS and SCEC, 1994).

Surface Faults

The Santa Monica Mountains are separated from Los Angeles and Santa Monica Basins by a system of W-striking surface faults. From east-to-west, the Raymond, Hollywood, and Santa Monica fault show evidence for post-Miocene and Holocene left-lateral slip (Wright, 1991; Dolan et al., 2000, Tsutsumi et al., 2001). The Santa Monica fault continues offshore at Potrero Canyon, where it has ~0.5 mm/yr north-side-up post-~120 ka reverse separation and an unknown left-lateral component (McGill, 1989; Dolan et al., 2000). Post-120 ka left-lateral slip is not known, but long-term slip is constrained by the 15 km left offset of the 8 Ma Tarzana Fan system (Wright, 1991; Redin, 1991). The Santa Monica fault splits into the coastal Malibu Coast fault and offshore Dume fault (Figs. 2, 3; Vedder et al., 1974; Nardin and Henyey, 1978; Junger and Wagner, 1977).

The southern front of the E-W Transverse Range orogen interacts with NW-SE right-lateral faults that cut the Peninsular Ranges and California Continental Borderland. Relative motion across the NW-striking faults may load the front west of intersections, or deform or offset faults along the front. In this case, earthquake segment boundaries can be expected at intersections. Alternatively, the two fault systems do not intersect, and right lateral slip is dissipated by clockwise rotation of local blocks so that the front is more uniformly loaded. The Palos Verdes fault projects into Santa Monica Bay from Palos Verdes Peninsula (Fig. 1). This fault has been the focus of shallow paleoseismologic study on the south side of Palos Verdes Peninsula, at Long Beach Harbor, where it has 2.7-3.0 mm/yr of post-7.8-8 ka right-lateral slip (McNeilan et al, 1996), or, based on geomorphic analysis in the same general area, has 2.5-3.8 mm/yr of post 120-80 ka right slip (Stephenson et al., 1995). A second NW-SE system of faults and folds, the San Pedro Basin fault zone, is mapped along the NE margin of deep Santa Monica bathymetric basin (Fig. 2; Junger and Wagner, 1977; Dartnell and Gardner, 1999; Fisher et al., 2001 and in revision for BSSA).

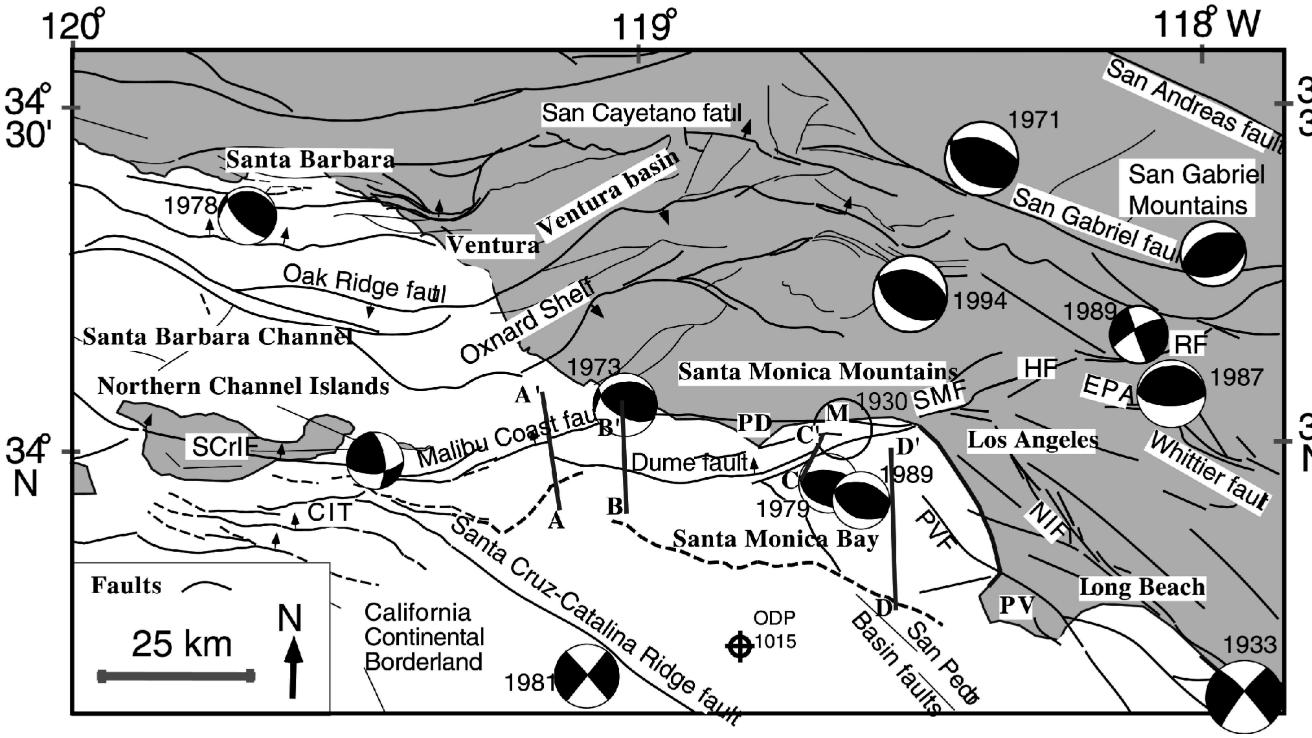

Figure 1: Faults, earthquakes, and locations. Lower hemisphere earthquake focal mechanisms from USGS and SCEC (1994), with location of 1930 earthquake (open circle) from Hauksson and Saldivar (1986). Mapping in onshore Ventura basin is from Hopps et al., 1995, and is on several subsurface horizons. Mapping in Los Angeles basin is from Wright (1991) and is on the base Repetto strata. Offshore mapping is by Sorlien and others (2000), and is on Miocene horizons, except south and east of the Northern Channel Islands faults are mapped at the seafloor. Mapping in northern Santa Barbara Channel is by us and is projected upwards to near the sea floor. Mapping in Santa Monica Bay is from this project. Other mapping from Jennings (1994). Profiles A, B, C, and D are shown in Sorlien et al., submitted to BSSA. CIT=zone of faults at tip of Channel Islands thrust, EPA=Elysian Park anticlinorium, NIF=Newport-Inglewood fault, PV=Palos Verdes, PVF=Palos Verdes fault, PD=Point Dume, SMF=Santa Monica fault. Dashed faults are blind.

The Shelf Projection and Santa Monica Mountains blind fault

The ranges, islands, and offshore banks of the western Transverse Ranges and Borderland have been interpreted as anticlinoria, and most of these anticlinoria are ascribed to thrust slip on blind faults (Davis and Namson, 1994; Davis et al., 1989; Shaw and Suppe, 1994, 1996; Seeber and Sorlien, 2000). The Santa Monica Mountains and the Shelf Projection are the two main anticlinoria in and adjacent to northern Santa Monica Bay (Fig. 2). The Shelf Projection anticlinorium, located immediately west of Manhattan Beach, is expressed by a prominent 15x10 km bathymetric high, (Fig. 2, Nardin and Henyey, 1978), and is larger, 20 x 20 km, in the subsurface. A blind fault that accounts for this structure would have similar dimensions and thus could generate an earthquake similar in size to the M6.7 Northridge quake. Although Nardin and Henyey (1978) suggested the anticlinorium was most active before 1 Ma, the shallowest strata are folded along its south edge.

Methods

We used three different overlapping grids of industry multichannel seismic reflection data, a few profiles from two other data sets, and an additional 800 m x 2500 m-spaced

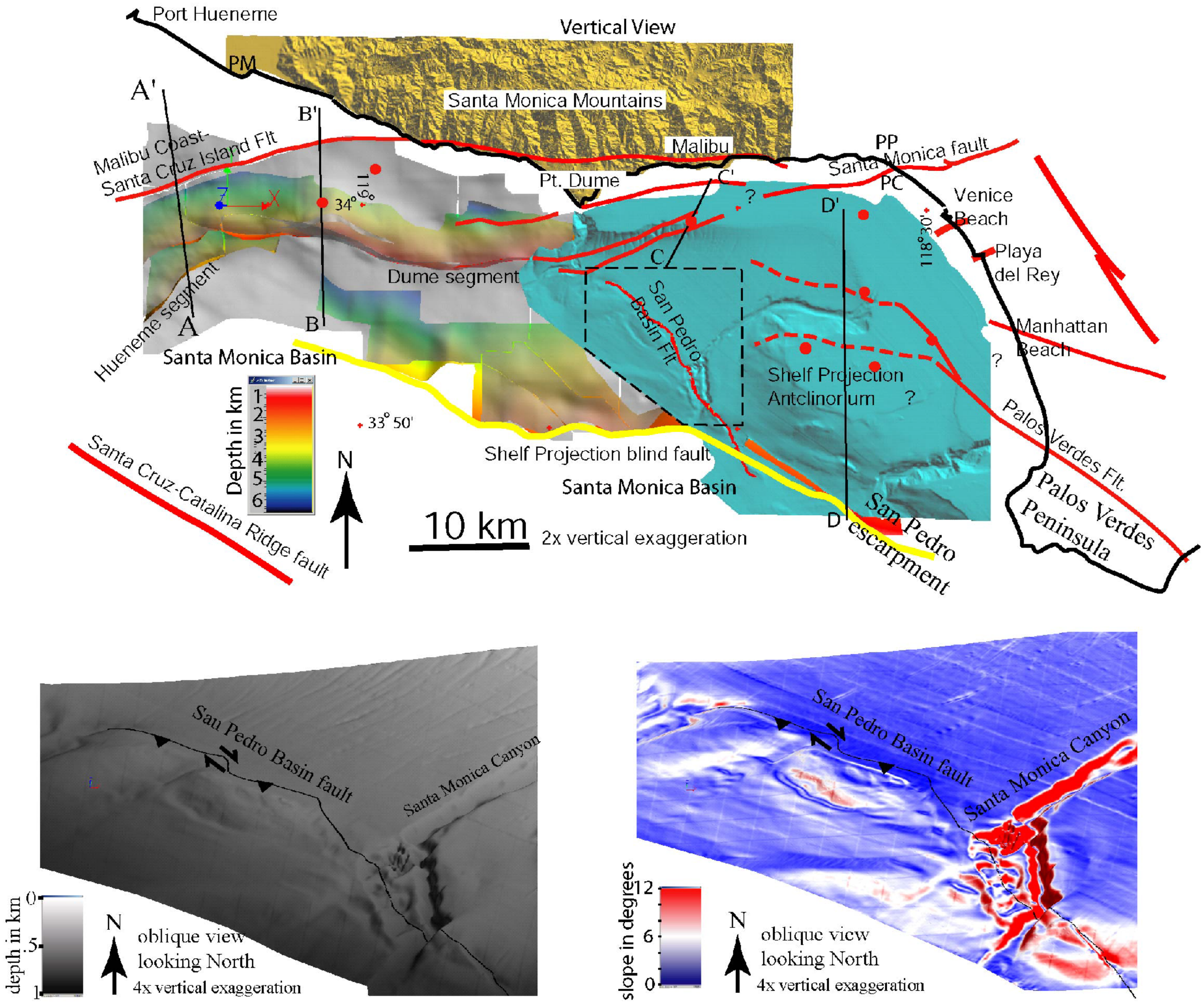

Figure 2: top: Vertical view of structure, bathymetry, and topography in and around Santa Monica Bay. This image was captured from our 3D model in GOCAD. USGS multibeam bathymetry is shown east of Pt. Dume (Dartnell and Gardner, 1999), and the lower Repetto horizon is shown as semi-transparent west of Pt. Dume. The Dume segment of the Santa Monica fault and the underlying Shelf Projection blind fault are shown as opaque in rainbow color scheme (0-6 km). The yellow curve is the upper (south) edge of the Shelf Projection blind fault; gaps below this edge are where we lack data. Red circles are wells where significant stratigraphic information was obtained and incorporated. Profiles B, C, D are shown in Sorlien et al. submitted. Not all faults are shown. Onshore faults from Wright (1991) and Dolan et al. (2000). PC=Potrero Canyon, PM=Point Mugu, PP=Pacific Palisades. **Bottom left**: Oblique view of seafloor-folding adjacent to the seafloor trace of the San Pedro Basin fault, shown as depth. Location is given by dashed black polygon at top. Folding occurs in the southwest hanging-wall of the fault. Right-lateral slip is indicated by folding associated with SE-striking restraining segments of the fault. Note that Santa Monica canyon entrenches growing folds, resulting in slope failure. **Bottom right:** same as bottom left except shown as slope draped on depth, with color scale in degrees.

grid of single channel sparker data to map structure and correlate stratigraphy through northern Santa Monica Bay. The single channel sparker data were acquired by industry for the U.S. Minerals Management Service (MMS) when they were part pf the U.S.G.S. (Burdick and Richmonds, 1982). Stratigraphic control was provided by logs from several wells drilled in the hanging-wall of the Dume fault, including 2 with sonic logs, and by other wells in the footwall farther east. The well information was converted to travel time and then correlated through the grids of reflection data, and around the east and west plunge of the Dume fault into the footwall

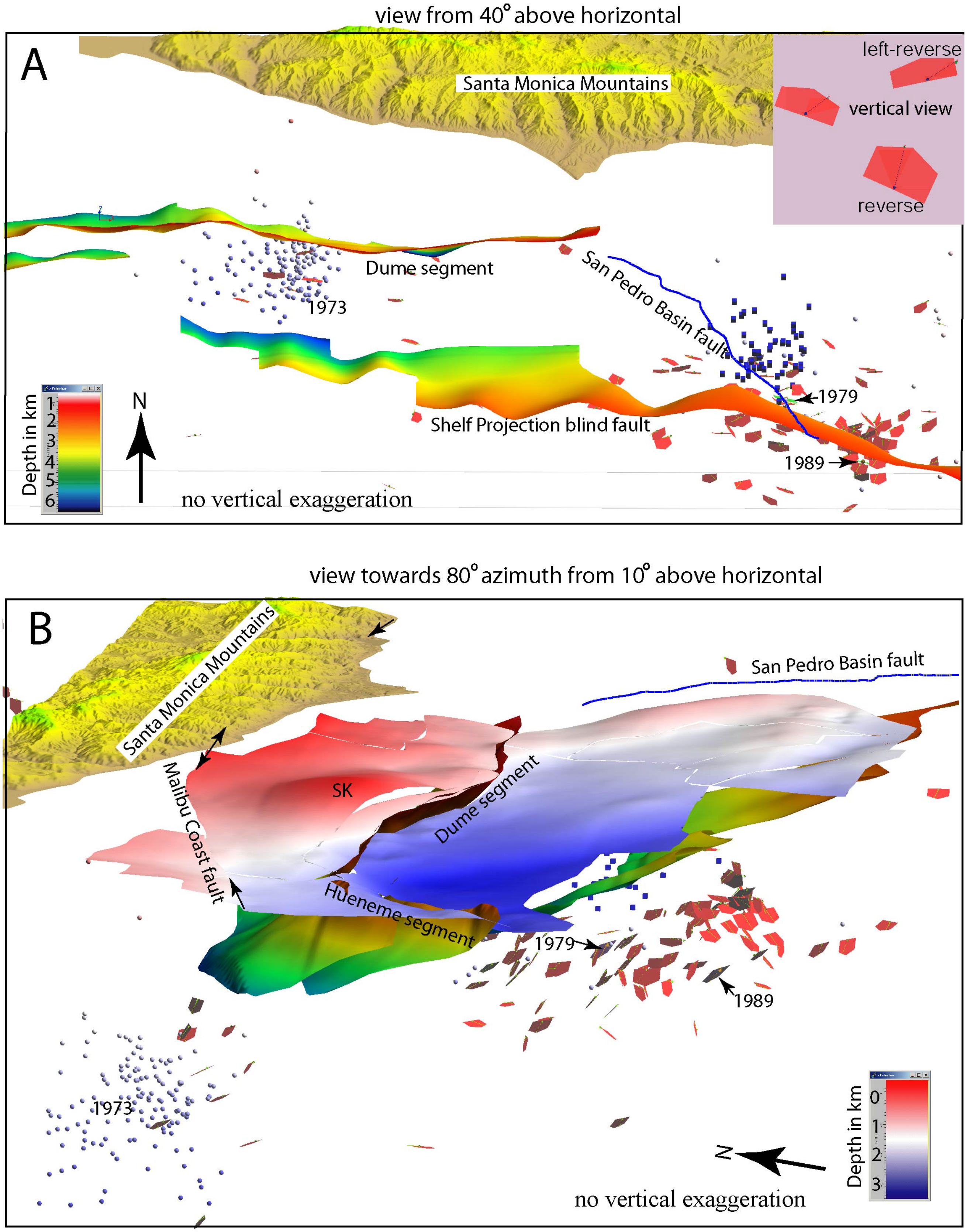

Figure 3A. Inclined view of Dume segment of Santa Monica fault and Shelf Projection blind fault. View is from 40 degrees above the horizontal. Color scale in lower left corresponds to depth in kilometers of faults in Figures 3A and 3B. The Dume segment dips slightly steeper than 40 degrees in its eastern part but flattens to the west. The Shelf Projection blind fault also flattens to the west, but its uppermost part dips less than 40 degrees along its entire strike. It is also possible that the Shelf Projection blind fault steepens at depth to project into the 1979 and 1989 mainshock hypocenters. Both faults, as well as the Malibu Coast fault to the north (not shown), project down to the 1973 Pt Mugu aftershock hypocenters (blue spheres labeled 1973; Stierman and Ellsworth, 1976).

Scattered earthquakes from 1977-1986 are also shown as blue spheres (Hauksson and Saldivar, 1989). Although the Dume segment projects near the Pt. Mugu aftershocks, so do the steeper Malibu Coast fault to the north, and the flatter Shelf Projection blind fault to the south. Blue cubes are aftershocks of the 1979 M5.0 reverse slip earthquake and are mostly between 7 and 10 km depth (Hauksson and Saldivar, 1986). The mainshock is labeled in its relocated position, as is the 1989 M5.0 earthquake (Hauksson, 1990). The inset shows our vertical view representation of earthquake slip planes in 3D. The long straight edge is horizontal and the point is downdip. Thin lines with arrowheads give slip of the hanging-wall. The bottom slip plane is reverse and the other two are oblique-reverse left-lateral. This representation is used in this figure and Figure 3B. Preferred slip planes of relocated earthquakes are shown; the horizontal edges of the M5 1979 and 1989 earthquakes are 1.4 km, while the downdip dimension is 1.0 km. The slip planes shown were relocated by John Armbruster and include aftershocks of the 1989 earthquake.

Figure 3B. Oblique view of deformed horizons and N-dipping structures. Oblique view towards 80˚ azimuth from 10˚ above horizontal; no vertical exaggeration. The lower Repetto horizon is shown in red, white, and blue colors, offset by left-reverse-oblique slip along the Dume Segment of the Santa Monica fault. Color scale in lower right corresponds to depth in kilometers of this horizon. All faults and earthquake hypocenters as in Figure 3A.

basin to the south. This correlation was supplemented by published information on seafloor outcrops (Vedder, 1990; Nardin and Henyey, 1978), and by stratigraphic and velocity information from coastal and offshore oil fields at Playa del Rey and Venice Beach (Cal Div. Oil and Gas, 1992).

RESULTS

Mapping and Map Restoration

We mapped a horizon within the lower part of the "Repetto" interval (Fig. 2). The unconformable base of Repetto Siltstone is between 4.42 +/- 0.57 m.y. and 3.4 +/- 0.3 m.y. (Blake, 1991), with the lower part missing where it onlaps growing folds. At Sycamore Knoll and in the deep basin beneath Hueneme Fan this horizon is over 500 m above the top Miocene. Therefore its age probably falls within the range for the base Repetto unconformity, or about 4 Ma. Reflections just below this horizon are parallel to it in both the hanging-wall and footwall of the Dume segment, indicating little seafloor relief at the time of deposition.

We used unfolding and map restoration to quantify strain due to faulting and folding of the ~4 Ma horizon. UNFOLD organizes grid points of the digital maps into adjoining triangles, lays each triangle flat, and then minimizes gaps and overlaps between triangles in an iterative process (Gratier et al, 1991, 1999). The flattened maps of each fault block are then manually fit together using a graphics software. Comparison between the restored and present state defines the finite displacement field with respect to a fixed reference line (Fig. 4). The details of the computer program UNFOLD and the technique of map restoration have been published (Gratier *et al*., 1991, 1999).

Interpretations

The overall strike of the offshore Santa Monica-Dume fault system is east-west, but it is arcuate, describing broad curves,. It can be divided into three segments based on strike: 1) the ENE-striking Santa Monica segment between Pt. Dume and its onshore intersection with the Newport-Inglewood trend; 2) the WNW-striking Dume segment; and 3) the partially blind set of NE-SW faults beneath the Hueneme submarine fan (Figs. 2, 3). The fault system is concave to the north through the Santa Monica and Dume segments, and concave to the south in the area between the Dume and Hueneme segments. The Dume segment links northwestward to the Malibu Coast fault via 2 subvertical strands with small vertical separation (tens of meters). We extended the structure contour map of the Dume segment an additional 10 km east as a fault trace map (Figs. 1, 2). The mapped Dume segment steps right about 1 km, not left, to the Santa Monica segment in the area southeast of Pt Dume (Fig. 2). The dominant N-dipping strand at C-C' (not shown, located on Fig. 2) aligns with the onshore Santa Monica fault at Potrero Canyon (also Vedder et al., 1974; and Nardin and Henyey, 1978).

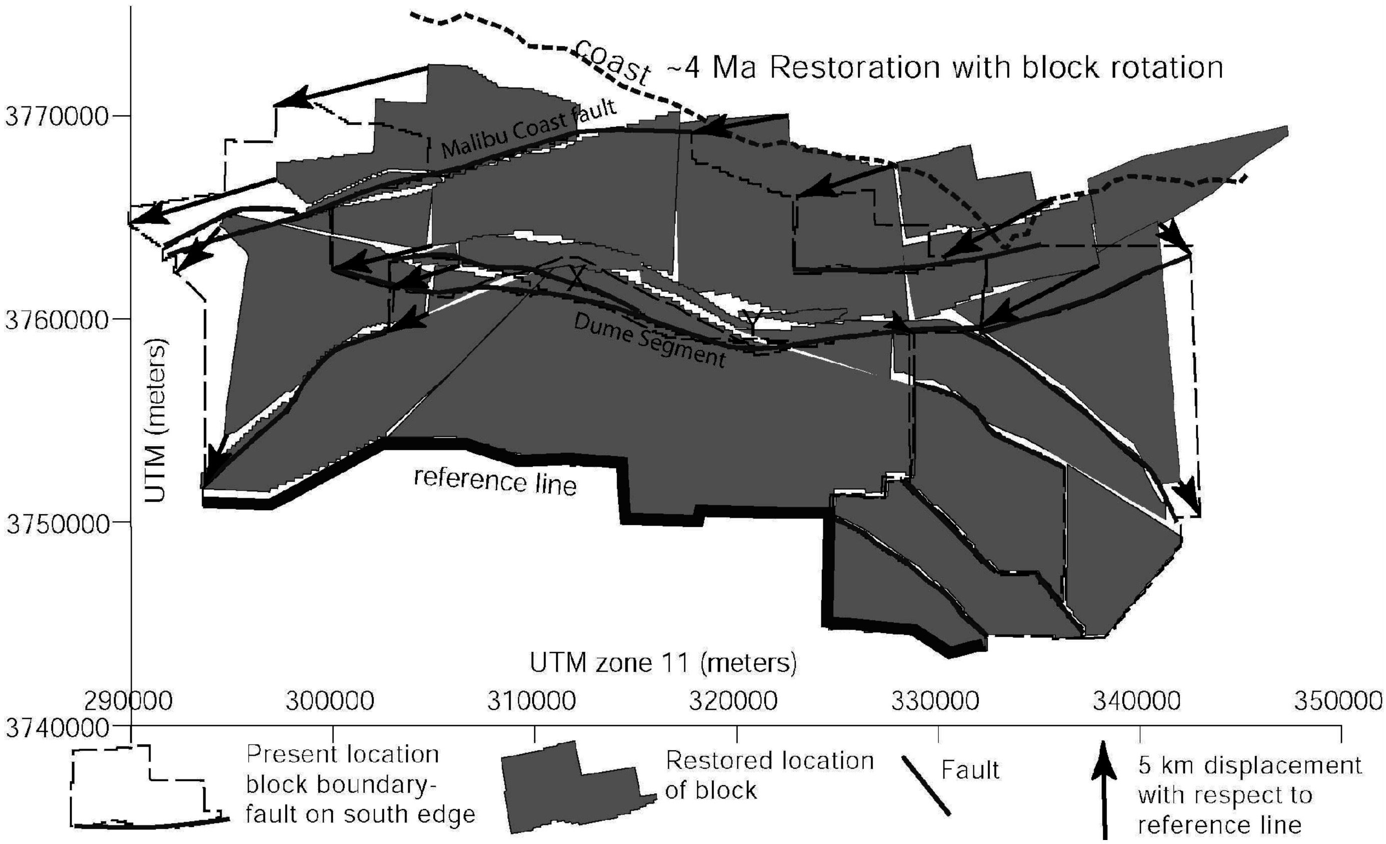

Figure 4: Preferred map restoration. The labeled dashed gray line is the coastline in its present position. The arrows connect the restored positions of corners of blocks to their present positions and represent finite displacement with respect to the reference line. Overlap of restored blocks at "X" suggests we overestimated contraction there, and gaps at "Y" suggest we underestimated contraction there. The deformed state of this map is shown in Figure 2, and faults are labeled there. Displacement across the Santa Monica-Dume fault is 7 km in the east and 4 km in the west; the variation is related to clockwise rotation in the east and counterclockwise rotation in the west.

The Dume segment dips moderately (40-50˚) north in its upper 4-6 km (Fig. 3). In the offshore area south and west of Point Mugu, the Malibu Coast fault strikes WSW, cutting the hanging-wall of the Dume fault. It is vertical above the Miocene volcanics (or equivalent) reflection, and within a few kilometers of A-A' (located in Fig. 2) has about 400 m N-side-up separation of that reflection and 200 m for the lower Repetto map horizon. We trace the Malibu Coast fault directly to the Santa Cruz Island fault (Fig. 1).

We interpret a blind gently-N-dipping fault beneath and south of the Dume fault. It preserves normal-separation in Miocene strata, and is interpreted as a Miocene low-angle normal fault. This fault is linked with or continuous with a NNE-dipping blind fault along the southern edge of the Shelf Projection anticlinorium (Fig. 2), and therefore we call it the Shelf Projection blind fault. This fault has been reactivated and is responsible for the post-Miocene folding. The south limb of the anticlinorium deforms the uppermost strata. The Shelf Projection bathymetric high, located offshore Manhattan Beach in eastern Santa Monica Bay, is about 10 x 15 km, while the anticlinorium exceeds 20 x 20 km in the subsurface. Assuming a local 40-50˚ north-northeast dip beneath its imaged uppermost part, the Shelf Projection blind fault projects into nodal planes of the 1979 and 1989 M5 reverse-slip earthquakes (Figs. 1, 3). It continues southeast beneath a broad southwest-dipping fold limb along the San Pedro escarpment.

Like Fisher et al. (2001), we interpret that the Palos Verdes fault does not intersect the Santa Monica-Dume fault, at least in Pliocene or younger strata. We map it to either bend to the west-northwest as a minor fault or to terminate against minor WNW faults (Fig. 2). In contrast, two strands of the San Pedro basin fault zone do intersect the Santa Monica-Dume fault. We interpret the Shelf Projection anticlinorium to be a blind thrust-fold structure forming a restraining stepover between the Palos Verdes and San Pedro Basin faults.

Reactivation and Basin Inversion

The Shelf Projection blind fault is part of the Miocene detachment system responsible for the ~90˚ of clockwise rotation of the western Transverse Ranges, including ~75˚ postdating the sampled mid-Miocene volcanic rocks in the Santa Monica Mountains (e.g., Kamerling and Luyendyk, 1979; Crouch and Suppe, 1993). The Santa Monica-Dume fault also shows evidence of Miocene extension. The interval between the top Miocene volcanics and the lower Repetto (Pliocene) map horizon is thicker in the upthrown hanging-wall of its Dume segment than in its footwall. Miocene sedimentary and volcanic rocks are very thick in the Santa Monica Mountains compared to very thin late Miocene strata present above basement in the topographically-low Playa del Rey area and in the adjacent offshore basin. (Schneider et al., 1996; Wright, 1991; Tsutsumi et al., 2001). The top of the Miocene is at about 1.5 km depth at the crest of the Venice and Playa del Rey oil fields at the coast (California Div. Oil, Gas, and Geothermal Resources, 1992), and in offshore wells (Sorlien et al., submitted). In contrast, cross sections show that the thickest post-Miocene strata (Repetto and Pico intervals) near the coast are located in a trough immediately south of the onshore Santa Monica fault (Wright, 1991; Tsutsumi et al., 2001). This trough or basin is continuous offshore, south of the Santa Monica fault and north of the Shelf Projection anticlinorium. The upper Miocene and part of lower Repetto interval pinch out in the area south of Pt. Dume. There, a strong reflection that may be the time equivalent of middle Miocene volcanic rocks, or else top Catalina schist, is overlain by Repetto Pliocene strata. In this area, the Repetto downlaps towards the south so that initial aggradation is time-transgressive. The basin is offset/interrupted in this area by a WSW-side-up strand of the San Pedro Basin fault zone, but continues and broadens westward to a post-Miocene depocenter beneath Hueneme Fan.

An independent correlation shows that upper Miocene strata are also missing in the footwall of the Santa Monica-Dume fault in the Hueneme Fan area. We correlated a top Miocene unconformity from a well on Sycamore Knoll (Fig. 3B) around the west plunge of the Dume segment fault-fold into its footwall, where the upper Miocene pinches out. Thus, there is an unconformity between middle Miocene or older rocks below and Pliocene Repetto strata above.

We assume that this unconformity formed near sea level because it is planar (except as deformed later), regional, and angular, associated with significant missing section. Submarine canyon erosion at depth does not form a smooth surface, and it may be unlikely that deep currentswould form a regional unconformity in this setting. Because the unconformity is now at 1.5 and 4 km depth, it must have subsided that amount if it indeed formed at sea level.

These observations are consistent with basin inversion due to transpressional post-Miocene reactivation of the Santa Monica-Dume fault (e.g., Seeber and Sorlien, 2000). A post-Miocene foreland basin has formed over what had been a footwall high. Folding of the Shelf Projection anticlinorium suggests that the Shelf Projection blind fault is also reactivated.

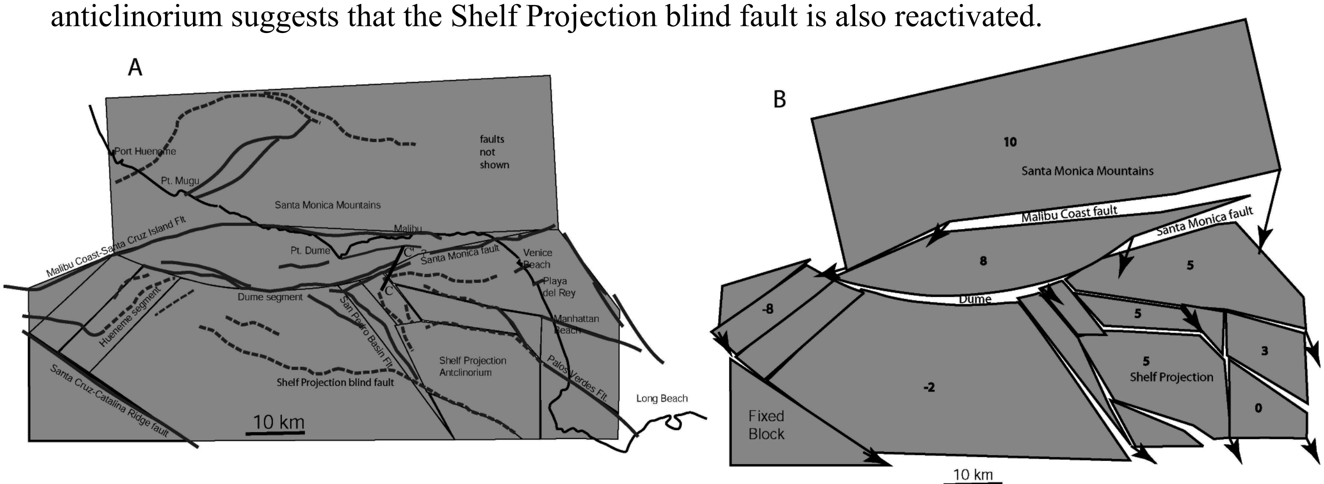

Figure 5: Simplified block model for Santa Monica Bay and vicinity. "A" shows the mapped fault pattern, dashed faults being blind, and the simplified block boundaries derived from that. "B" shows restored positions, roughly similar to the 4 Ma restoration in Figure 4. Positive numbers are amount of clockwise rotation and negative numbers are amount of counterclockwise rotation. Gaps represent shortening, and arrows represent displacement with respect to the fixed block. Variations of the simplified block model from the actual geometry, internal deformation of blocks, omission of thrust overlaps across faults, and the lack of unfolding, all change the modeled contraction and displacements. But, large-scale patterns such as the relation of left slip on the Santa Monica-Dume fault to rotation of the Santa Monica Mountains are revealed.

Deformation Models

Contraction across the Santa Monica-Dume fault varies depending on its strike: it is large across the WNW-striking segment and low across the eastern, ENE-striking segment. These variations can be accounted for by uniform slip on the fault, provided the slip is nearly parallel to the eastern segment. Predominantly left-lateral slip along the ENE-striking offshore segment is responsible for transpression in its WNW-striking section. Thus, the WNW-striking Dume segment is a restraining segment in the Santa Monica fault. Similarly, there is little structural relief across the subvertical ENE-striking offshore part of the Malibu Coast fault across Hueneme Fan, while its E-W onshore segment along the Santa Monica Mountains displays a north dip and subvertical and overturned Monterey Formation (Dibblee and Ehrenspeck, 1993).

These qualitative kinematic interpretations were tested and quantified using a map restoration technique. Maps of fault-bounded pieces of the Pliocene horizon were restored to a horizontal state with UNFOLD. The flattened pieces were then assembled with respect to a southern reference line. Vertical-axis rotation is allowed along with limited internal deformation of blocks. The trace of the Santa Monica-Dume fault (map view) is curved in map view, being concave-north along ~40 km (Figs. 4, 5). If slip was pure left-lateral along this entire length, the Santa Monica Mountains block to the north would rotate clockwise relative to the Borderlands block to its south. In support of this model, paleomagnetic data indicate at least 75∞ of clockwise rotation of the Santa Monica Mountains since eruption of the middle Miocene Conejo Volcanics there (Kamerling and Luyendyk, 1979). GPS data indicate current clockwise rotation of the Santa Monica Mountains block at 7 +/-1 deg/m.y. (Donnellan et al., 1993). We thus restore deformation assuming a clockwise rotation in the hanging-wall block of the Santa Monica-Dume fault.

We hypothesize counter-clockwise rotation near the bend between the Dume and Hueneme segments. The Santa Monica-Dume fault has a greater left-lateral slip component adjacent to clockwise rotating blocks than adjacent to counter-clockwise rotating blocks. The restoration in Figure 4 shows about 7 km of left-lateral slip in the east and about 4 km in the west. About 0.5 km of this slip is absorbed in the west plunge of the Sycamore Knoll anticline and does not reach the Hueneme Fan area. Right-lateral slip on two strands of the San Pedro Basin fault is 1.9 km in this fitting, as opposed to zero in a fitting with no rotations (not shown, see Sorlien et al., submitted).

Slip partitioning between right-lateral Borderlands faults and vertical axis block rotation
We constructed a simplified block model in order to examine the kinematics of block rotations and fault terminations beyond the area of our lower Repetto horizon mapping (Fig. 5). This block model incorporates our fault mapping as well as published fault mapping, but blocks are simplified to polygons. We qualitatively retrodeform this block model to investigate regional patterns of deformation (Fig. 5). Right-lateral slip is transferred between the Palos Verdes fault and the northern San Pedro Basin fault by contraction in the Shelf Projection restraining step. The block model includes clockwise rotation of Shelf Projection block and of the basin blocks between it and the Santa Monica Mountains. Part of the right-lateral slip on the Palos Verdes fault is dissipated into clockwise rotation and part is transferred to the northern San Pedro Basin fault.

Hazard from distributed faulting in rotating system
If the ~3 mm/yr of post-~8 ka right-lateral slip on the Palos Verdes fault (McNeilan et al., 1996) were absorbed by contraction across the Shelf Projection anticlinorium with no block rotation, the blind fault(s) beneath it would accumulate about 1 m of contraction (1.15 m of slip on 30 deg dipping fault) every ~330 years. The pattern of thrust loading would be different if blocks rotate. Our simplified block model includes 5 deg clockwise rotation of the Shelf Projection and of blocks to its north. A system of clockwise rotating elongate blocks includes left-lateral oblique slip between the blocks, and can include both extension and contraction where space problems manifest (Luyendyk, 1991). In such a system, many faults may be active at lower slip rates. The hazard from such a system for damaging earthquakes is large because earthquakes will be common (as has been observed historically), but they will also be distributed and the maximum magnitude not as large. Additionally, if right-lateral slip is transformed into clockwise rotation or distributed

shear, the right-lateral system can end or become blind, and need not segment the Santa Monica-Dume fault. In this case, a large onshore-offshore rupture on the Santa Monica-Dume fault, although rare (e.g., Dolan et al., 2000), is probable.

Fault area and Maximum Magnitude

The only major segment boundary of the Santa Monica-Dume fault is 55 km west of Potrero Canyon, where the Dume fault segment becomes mostly blind near the Hueneme segment. Subvertical faults in this area with small vertical separation connect the Dume and Malibu Coast fault. We assume that intersections with the San Pedro Basin fault system near Point Dume and a <1 km right step in the shallow Santa Monica-Dume fault in that area need not stop a rupture. Thus, the Santa Monica-Dume fault is 65 km-long between the Hueneme segment and the left step at the West Beverly Hills lineament (aligned with Newport-Inglewood fault, Dolan et al., 2000). One caution is that we do not now have data that cross the fault in the 14 km west of the coast, and rely there on earlier mapping (Dolan et al., 2000; Nardin and Henyey, 1978, Osborne et al., 1980). We use a dip of 45 deg and a depth of 20 km to project Santa Monica fault beneath the Northridge hypocenter (as was done by Tsutsumi et al., 2001). The fault width is 28 km and its area is 1840 sq km. Using the rupture area-Magnitude relation for California earthquakes of Dolan et al. (1995), the maximum Magnitude for the Santa Monica-Dume fault is 7.35. Using the rupture area-Magnitude relation of Wells and Coppersmith (1994) for global earthquakes results in a maximum Magnitude of 7.25.

We cannot model a late Quaternary blind thrust component of slip along the Santa Monica-Dume fault without more information on late Quaternary folding of the Santa Monica Mountains. It is premature to calculate a maximum magnitude for the Shelf Projection fault until it is known how much of it has been reactivated and remains active, and until the map of its uppermost part along the Shelf Projection anticlinorium can be continued to greater depth. However, if 3 mm/yr of Palos Verdes fault-right slip were absorbed by thrusting without block rotation, a Northridge-sized earthquake would occur every 330 years. Alternatively, smaller, much more frequent earthquakes are associated with distributed deformation. The 1.5 to 4 km of post-Miocene subsidence in the footwall of the Santa Monica-Dume fault, combined with erosion of the Santa Monica Mountains (e.g., Meigs et al., 1999) means that increase in structural relief is much greater than surface uplift. If footwall subsidence continues today, use of late Quaternary uplifted marine terraces to estimate slip on blind thrust faults may result in underestimation of the hazard.

Data efforts, sound levels, and siting USGS reflection profiles

We also have been working on three related projects. The first is working with Chevron-Texaco and with SCEC to find a way to preserve and make public their offshore west coast seismic reflection data. The second is working with Mike Fisher and Bill Normark of USGS to carefully site profiles for their June 2002 field program. The third was investigating sound levels and permitting to acquire seismic reflection data and multibeam bathymetry in a cruise of opportunity (permitting related to marine mammals). This was time-consuming for one of us (C.C.S.), and data acquisition was cancelled in advance because of equipment problems (the cruise was always intended as a test of equipment). However, the investigations on sound levels and permitting are not wasted as we have submitted proposals to use acoustic sources in the

California Borderland.

CONCLUSIONS

The Santa Monica and Dume faults are part of the same fault system, and are probably directly connected. The interval between the mapped Pliocene horizon and the top Miocene volcanics is thicker on the upthrown hanging-wall side of both onshore and offshore segments of the fault, which is consistent with basin inversion. Folding along the Dume segment initiated during the Pliocene Repettian Stage and accelerated towards the end of this stage. Left-lateral slip on the ENE-striking Santa Monica segment results in contraction across the offshore Dume restraining segment. Incorporating reasonable rates of clockwise rotation of the Santa Monica Mountains in a map restoration (including some distortion) results in an estimate of 4-7 km of left slip in the last ~4 m.y., and 1.8 km of right slip on the San Pedro Basin fault zone. Alternatively, but less probably, a restoration with no vertical axis rotation and no distortion of fault blocks produces an estimate of 3 km of left slip, and no right slip on the San Pedro Basin fault zone. The Palos Verdes fault does not have any obvious effect on the continuity of the Santa Monica Dume fault, and the two systems do not intersect at or above the Pliocene map horizon. Strands of the San Pedro Basin fault zone intersect the Dume fault, but do not appear to offset it. There is a <1 km right step and a small increase to the west in vertical separation across the Santa Monica-Dume fault in the general area of this intersection. Maximum magnitude for an earthquake on the Santa Monica-Dume fault is 7.35 based on a rupture area-Magnitude relationship for California. A blind fault that dips north beneath the Shelf Projection anticlinorium extends at least 50 km beneath Santa Monica Bay, and is a Miocene low-angle normal fault partially reactivated as a thrust fault.

ACKNOWLEDGMENTS

Jean-Pierre Gratier provided his software and assistance in its use. Drew Mayerson and others at the U.S. Minerals Management Service provided access to the Digicon data, Tom Wright's and David Okaya's efforts made the Exxon data available to SCEC researchers, other industry sources provided additional data. John Armbruster did the earthquake relocations. Work by Mike Fisher, Bill Normark, and others at USGS first noted the possibility that the northern Palos Verdes fault was inactive or not present, and the extreme youth of folding along the San Pedro Basin fault. Bruce Luyendyk is supervising Kris Broderick's thesis. Information on petroleum wells along the Los Angeles area coast was found in the repository at Long Beach State operated by Dan Francis. Funded by USGS-NEHRP contract 02HQ GR0013. Mapping in northwest Santa Monica Bay has been supported by SCEC.

REFERENCES

Argus, D. F., Heflin, M. B., Donnellan, A., Webb, F. H., Dong, D., Hurst, K. J., Jefferson, D. C., Lyzenga, G. A., Watkins, M. M., and Zumberge, J. F., 1999, Shortening and thickening of metropolitan Los Angeles measured and inferred by using geodesy, Geology, v. 27, p. 703-706.

Blake, G. H., 1991, Review of the Neogene biostratigraphy and stratigraphy of the Los Angeles Basin and implications for basin evolution, in K.T. Biddle, ed., Active Margin Basins, AAPG Memoir 52, American Association of Petroleum Geologists, Tulsa, p. 135-184

Burdick, D. J., and Richmond, W. C., 1982, A summary of geologic hazards for proposed OCS oil and gas lease sale 68, Southern California, MMS and USGS Open-File Report 82-33
California Division Oil, Gas, and Geothermal Resources, 1992, California Oil & Gas Fields, Volume II: Southern, Central Coastal, and Offshore California, Pub. TR11.
Dartnell, P., and Gardner, J. V., 1999, Sea-Floor Images and Data from Multibeam Surveys in San Francisco Bay, Southern California, Hawaii, the Gulf of Mexico, and Lake Tahoe, California-Nevada, Digital Data Series DDS-55 Version 1.0.
Davis, T. L., and Namson, J. S., 1994, A balanced cross-section of the 1994 Northridge earthquake, southern California, Nature, vol. 372 p. 167-169.
Davis, T. L., Namson, J., and Yerkes, R. F., 1989, A cross section of the Los Angeles Area: Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard, Journal of Geophysical Research, vol. 94, no. B7, p. 9644-9664.
Dibblee, T. W. Jr, and Ehrenspeck, H. E., 1993, Geologic Map of the Point Dume quadrangle, Los Angeles and Ventura Counties, California, H. E. Ehrenspeck, ed., Dibblee Geological Foundation, Santa Barbara, California, scale 1:24,000.
Dolan, J. F., Sieh, K. E., and Rockwell, T. K, 2000, Late Quaternary activity and seismic potential of the Santa Monica fault system, Los Angeles, California, Geological Society of America, v. 112, p. 1559-1581.
Dolan, J. F., Sieh, K. E., Rockwell, T. K., Yeats, R. S., Shaw, J., Suppe, J., Huftile, G. J., and Gath, E. M., 1995, Prospects for larger or more frequent earthquakes in the Los Angeles metropolitan region, Science, vol. 267, p. 199-205.
Donnellan, A., Hager, B. H., King, R. W., and Herring, T. A., 1993a, Geodetic measurement of deformation in the Ventura Basin region, southern California, Journal of Geophysical Research, vol. 98, no. B12, p. 21,727-21,739.
Fisher, M. A., Normark, W. R., Bohannon, R. G., Sliter, R. W., Calvert, A. J., 2001, Geology of the continental margin beneath Santa Monica Bay, southern California, from small-airgun, seismic-reflection data, Eos. Trans. AGU, 82(47), Fall Meet. Suppl., Abstract S11A-0544, p. F804.
Fisher, M. A., Normark, W. R., Bohannon, R. G., and Sliter, R. W., Geology of the continental margin beneath Santa Monica Bay, southern California, from seismic reflection data, in revision for Bulletin of the Seismological Society of America.
Gratier, J.-P., Guillier, B., Delorme, A., and Odonne, F., 1991, Restoration and balance of a folded and faulted surface by best-fitting of finite elements: principle and applications, Structural Geology, vol. 13, no. 1, p.111-115.
Gratier, J.-P., Hopps, T., Sorlien, C. C., and Wright, T., 1999, Recent crustal deformation in southern California deduced from the restoration of folded and faulted strata, Journal of Geophysical Research, v. 104, p. 4887-4899.
Gutenberg, B., Richter, C. F., and Wood, H. O., 1932, The earthquake in Santa Monica Bay, California, on August 30, 1930, Bulletin Seismological Society of America, V. 22, p.138-154.
Hauksson, E. and Saldivar, G. V., 1986, The 1930 Santa Monica and the 1979 Malibu, California, earthquakes, Seismological Society of America Bulletin, v. 76, p. 1542-1559.
Hauksson, E., 1990, Earthquakes, faulting, and stress in the Los Angeles Basin, Journal of Geophysical Research, vol. 95, no. B10, p. 15365-15394.

Hopps, T.E., H.E. Stark and R.J. Hindle, 1995, Subsurface data in basin analysis: An example from Ventura Basin, California, SCEC Workshop: Thrust Ramps and Detachment Faults in the Western Transverse Ranges, UC Santa Barbara, p. 10.

Jennings, C. W., 1994, Fault activity map of California and adjacent areas with locations and ages of recent volcanic eruptions, California Division of Mines and Geology, Geologic Data Map no. 6 scale 1:750,000.

Junger, A., and Wagner, H. C., 1977, Geology of the Santa Monica and San Pedro Basins, California continental borderland: U. S. Geological Survey Misc. Field Studies Map MF-820, 10 p. 5 pls., map scale 1:250,000.

Kamerling, M. J., and Luyendyk, B.P., 1979, Tectonic rotations of the Santa Monica Mountains region western Transverse Ranges, California, suggested by paleomagnetic vectors, Geological Society of America Bulletin, Part 1, vol. 90, p. 331-337.

Luyendyk, B.P., 1991, A model for Neogene crustal rotations, transtension, and transpression in southern California, Geological Society of America Bulletin, v. 103, p. 1528-1536.

McGill, J. T., 1989, Geologic maps of the Pacific Palisades area, Los Angeles, California, U. S. Geological Survey Map I-1828, scale 1:4,800.

McNeilan, T. W., Rockwell, T. K., Resnick, G. S., 1996, Style and rate of Holocene slip, Palos Verdes fault, southern California: Journal of Geophysical Research, v. 101, p. 8317-8334.

Meigs, A., N. Brozovic, and M. L. Johnson (1999). Steady, balanced rates of uplift and erosion of the Santa Monica Mountains, California: *Basin Research* **11**, 59-73.

Nardin, T. R., and Henyey, T. L., 1978, Pliocene-Pleistocene diastrophism of Santa Monica and San Pedro shelves, California Continental Borderland, American Association of Petroleum Geologists Bulletin, v. 62, p. 247-272.

Osborne, R. H., Scheidemann, R. C. Jr., Nardin, T. R., and Harper, A. S., 1980, Quaternary stratigraphy and depositional environments, Santa Monica Bay, Southern California, *in* Field, M. E., et. al., eds., Quaternary Depositional Environments of the Pacific Coast: Pacific Coast Paleogeography Symposium 4: Los Angeles, California, The Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 143-156.

Redin, T., 1991, Oil and gas production from submarine fans of the Los Angeles basin, in K.T. Biddle, ed., Active Margin Basins, AAPG Memoir 52, American Association of Petroleum Geologists. P. 239-259.

Schneider, C. L., C. Hummon, R. S. Yeats, and G. L. Huftile (1996). Structural Evolution of the northern Los Angeles basin, California, based on growth strata, *Tectonics* 15, 341-355.

Seeber, L, and Sorlien, C. C., 2000 Listric thrusts in the western Transverse Ranges, California, Geological Society of America Bulletin, v. 112, p. 1067-1079.

Shaw, J. H., and Suppe, J., 1994, Active faulting and growth folding in the eastern Santa Barbara Channel, California, Geological Society of America Bulletin, vol. 106, p. 607-626.

Shaw, J. H., and Suppe, J., 1996, Earthquake hazards of active blind-thrust faults under the central Los Angeles basin, California, Journal of Geophysical Research, vol. 101, no. B4, p. 8623-8642.

Shipboard Scientific Party, 1997, 9. Site 1015, in Proceedings of the Ocean Drilling Program, Initial Reports, v. 167, Lyle, M., Koizumi, I., and Richter, C., eds., p. 223-237.

Sorlien, C. C., Gratier, J. P., Luyendyk, B.P.,Hornafius, J. S., and Hopps, T. E, 2000, Map restoration of folded and faulted late Cenozoic strata across the Oak Ridge fault, onshore and offshore Ventura basin, California, Geological Society of America Bulletin, v. 112, p. 1080-1090.

Stephenson, W. J., Rockwell, T. K., Odum, J. K., Shedlock, K. M. and Okaya, D. A.,1995, Seismic reflection and geomorphic characterization of the onshore Palos Verdes fault zone, Los Angeles California: Bulletin of the Seismological Society of America, v. 85, p. 943-950.

Stierman, D. J., and Ellsworth, W. L., 1976, Aftershocks of the February 21, 1973 Point Mugu, California earthquake, Bulletin of the Seismological Society of America, vol. 66, no. 6, p. 1931-1952.

Tsutsumi, H., Yeats, R. S., and Huftile, G. J., 2001, Late Cenozoic tectonics of the northern Los Angeles fault system, California, Geological Society of America Bulletin, v. 113, p. 454-468.

U. S. Geological Survey and Southern California Earthquake Center, Scientists of, 1994, The magnitude 6.7 Northridge, California earthquake of 17 January, 1994, Science 266, p. 389-397.

Vedder, J. G., Beyer, L. A., Junger, A., Moore, G. W., Roberts, A. E., Taylor, J. C., and Wagner, H. C., 1974, Preliminary report on the geology of the Continental Borderland of southern California, U. S. Geological Survey Misc. Field Studies Map MF-624, 34 pages and 9 plates.

Vedder, J. G., 1990, Maps of California Continental Borderland showing compositions and ages of samples acquired between 1968 and 1979, U. S. Geological survey Miscellaneous Field studies Map, Map MF-2122.

Wells, D. L., and Coppersmith, K. J., 1994, New empirical relationships among Magnitude, rupture length, rupture width, rupture area, and surface displacement, Bulletin of the Seismological Society of America, v. 84, p. 974-1002.

Wood, H. O., 1933, Preliminary report on the Long Beach earthquake, Bulletin of the Seismological Society of America, v. 23, p. 43-56.

Wright, T. L., 1991, Structural geology and tectonic evolution of the Los Angeles Basin, California: *in* K. T. Biddle, ed., Active margin basins; AAPG, Memoir 52, p. 35-134.

Abstracts from this project:

Sorlien, C. C., Kamerling, M. J., and Seeber, L., 2001, The Dume fault, northern Santa Monica Bay, California, EOS Trans. AGU, Fall Meet. Suppl., v. 82, p. F802.

Broderick, K., Sorlien, C. C., Kamerling, M. J., Seeber, L., and Luyendyk, B. P., 2002, Post-Miocene Faulting and Folding in the Southwestern Transverse Ranges, Santa Monica Bay, California, Eos. Trans. AGU, v. 83, Fall Meet. Suppl., Abstract.

Sorlien, C. C., Broderick, K., Kamerling, M. J., Fisher, M., and Seeber, L., 2002, A blind fault beneath Santa Monica Bay, Proceedings and Abstracts, Southern California Earthquake Center Annual Meeting, p. 132.

Invited Talk

Sorlien, C. C., Broderick, K., Kamerling, M. J., Fisher, M., Normark, W., Sliter, R., and Seeber, L, 2003, Structure and kinematics beneath Santa Monica Bay, California, Pacific Section AAPG abstracts, May 2003, Long Beach.

Abstract on similar structure:

Sorlien, C.; Imren, C. ; Cormier, M.; Seeber, L.; Steckler, M. ; Emre, O.; Okay, A.; Kuscu, I., 2003, Regional contractional anticlines within the North Anatolian fault system, southeast Marmara Sea, Turkey?, EGS - AGU - EUG Joint Assembly, Nice, France, April 2003, Geophysical Research Abstracts, Volume 5, 2003.

Submitted manuscript

Sorlien, C. C., Pinter, N, Kamerling, M. J., Seeber, L., and Broderick, K., The Santa Monica-Dume fault system in northern Santa Monica Bay, California, submitted to Bulletin of the Seismological Society of America.

Data Availability

Well data, including sonic surveys, are public and available from Industry sources such as Rileys, or from the California Division of Oil and Gas in Long Beach, or from us. Wells in Federal waters (more than 5 km from the coast) are usually available from the US Minerals Management Service in Camarillo, but the wells in Santa Monica Bay all predate 1970 and the MMS may not have information on them. The 800x2500 m grids of single channel sparker data are described in Burdick and Richmond (1982), but are apparently are missing from the sets of microfilm available from the NGDC. The originals can be found with difficulty from the US Minerals Management Service, but it is probably simpler to contact us. A 2.5 km by 2.5 km grid of non-migrated mid-1970s-vintage multichannel seismic reflection data from Digicon has been released by the U.S. Minerals Management Service and the films are in Camarillo. A grid of migrated seismic reflection data from Exxon is available from the Southern California Earthquake Center for research purposes (contact David Okaya). Other industry seismic reflection data used in this project are not available. The profiles A-A’ through D-D’ located in this report are not shown here due to their large file size, but are in our submitted manuscript (BSSA). Our digital structure-contour maps of faults have been, and are being provided to the SCEC Community Fault Model. This model is being produced by Andreas Plesch and John Shaw and others at Harvard, and will be released in early 2003. It will be likely linked to www.scec.org. Contact Christopher Sorlien at chris@crustal.ucsb.edu for additional information on data.